

Evidence for a companion to BM Gem, a silicate carbon star¹

Hideyuki Izumiura^{2,10}, Kunio Noguchi³, Wako Aoki³, Satoshi Honda³, Hiroyasu Ando³,
Masahide Takada-Hidai⁴, Eiji Kambe⁵, Satoshi Kawanomoto⁶, Kozo Sadakane⁷, Bun'ei
Sato^{8,2}, Akito Tajitsu⁹, Wataru Tanaka³, Ki'ichi Okita², Etsuji Watanabe², and Michitoshi
Yoshida²

ABSTRACT

Balmer and Paschen continuum emission as well as Balmer series lines of P Cygni-type profile from H_γ through H_{23} are revealed in the violet spectra of BM Gem, a carbon star associated with an oxygen-rich circumstellar shell (“silicate carbon star”) observed with the high dispersion spectrograph (HDS) on the Subaru telescope. The blue-shifted absorption in the Balmer lines indicates the presence of an outflow, the line of sight velocity of which is at least 400 km s⁻¹, which is the highest outflow velocity observed to date in a carbon star. The Balmer lines showed a significant change in profile over a period of 75 days. Strong Ca II K emission was also detected, while Ca II H emission, where $H\epsilon$ overlapped, was absent on both observation occasions. Violet spectra of the other two silicate carbon stars, V778 Cyg and EU And, and of the prototypical J-type carbon star, Y CVn, were also observed, but none of these were detected in either continuum emission below 4000 Å or Balmer lines. We argue that the

²Okayama Astrophysical Observatory, National Astronomical Observatory, Kamogata, Asakuchi, Okayama 719-0232, Japan

³Division of Optical and Infrared Astronomy, National Astronomical Observatory, Mitaka, Tokyo 181-8588, Japan

⁴Liberal Arts Education Center, Tokai University, Hiratsuka, Kanagawa 259-1292, Japan

⁵Department of Earth and Ocean Sciences, National Defense Academy, Yokosuka, Kanagawa 239-8686, Japan

⁶Astronomical Data Analysis Center, National Astronomical Observatory, Mitaka, Tokyo 181-8588, Japan

⁷Astronomical Institute, Osaka Kyoiku University, Kashiwara, Osaka 582-8582, Japan

⁸Graduate School of Science and Technology, Kobe University, Kobe, Hyogo 657-8501, Japan

⁹Subaru Telescope, National Astronomical Observatory of Japan, 650 North A'ohoku Place, Hilo, HI 96720, USA

¹⁰ e-mail: izumiura@oao.nao.ac.jp

observed unusual features in BM Gem are strong evidence for the presence of a companion, which should form an accretion disk that gives rise to both an ionized gas region and a high velocity, variable outflow. The estimated luminosity of ~ 0.2 (0.03 – 0.6) L_{\odot} for the ionized gas can be maintained by a mass accretion rate to a dwarf companion of $\sim 10^{-8} M_{\odot} \text{ yr}^{-1}$, while $\sim 10^{-10} M_{\odot} \text{ yr}^{-1}$ is sufficient for accretion to a white dwarf companion. These accretion rates are feasible for some detached binary configurations on the basis of the Bond-Hoyle type accretion process. Therefore, we concluded that the carbon star BM Gem is in a detached binary system with a companion of low mass and low luminosity. However, we are unable to determine whether this companion object is a dwarf or a white dwarf, although the gas outflow velocity of 400 km s^{-1} as well as the non-detection in the X-ray survey favor its identity as a dwarf star. The upper limits for binary separation are 210 AU and 930 AU for a dwarf and a white dwarf, respectively, in the case of circular orbit. We also note that the observed features of BM Gem mimic those of Mira (*o* Cet), which may suggest actual similarities in their binary configurations and circumstellar structures.

Subject headings: stars: AGB and post-AGB—stars: carbon—stars: evolution—stars: mass loss—stars: winds, outflows—accretion—individual (BM Gem, V778 Cyg, EU And, Y CVn, Mira)

1. INTRODUCTION

When low- and intermediate-mass stars evolve along the asymptotic giant branch where double shell burning of He and H takes place in the interior, the He burning becomes unstable and gives rise to periodic thermonuclear runaway (“thermal pulse” or “He shell flash”), which induces mixing of newly synthesized ^{12}C and other processed materials at the surface (third dredge-up, Iben 1975; Sugimoto & Nomoto 1975). The mixing gradually enhances the surface abundance of carbon, which will eventually turn a star originally oxygen-rich in the surface chemical composition into a carbon star (cf. Iben & Renzini 1983).

Among cool luminous carbon stars, there are a group of stars that show silicate dust emission features in the mid-infrared at 10 and $18 \mu\text{m}$ (Little-Marengo 1986; Willems & de Jong 1986); these are the so-called “silicate carbon” stars. Silicates are the signature of

¹Based on data collected at the Subaru Telescope, which is operated by the National Astronomical Observatory of Japan

oxygen-rich chemistry in their circumstellar dust shells, while their optical spectra dominated by molecular absorption bands of C_2 and CN show that their atmospheres are carbon-rich. The oxygen-rich chemistry in their circumstellar envelopes is also confirmed in the gas-phase by the detection of water vapor masers at 22 GHz (Benson & Little-Marenin 1987; Nakada et al. 1987). Even carbon-rich objects showing crystalline silicate features have been discovered (Waters et al. 1998; Molster et al. 2001).

The intriguing co-existence of oxygen-rich and carbon-rich chemistries in a single system prompted two hypothetical explanations. One was the binary system consisting of a carbon star and a dust-enshrouded M-type giant (OH/IR) star (Benson & Little-Marenin 1987; Little-Marenin, Benson, & Dickinson 1988). The other was more interesting, i.e., that we are witnessing a brief evolutionary stage where the star is in transition from an oxygen-rich star to a carbon star by the third dredge-up while the remnant oxygen-rich dust shell is still visible (Willems & de Jong 1986, 1988). These earlier pictures were, however, discarded based on the absence of both spectroscopic signatures of a luminous M-type (OH/IR) companion (Noguchi et al. 1990; Lambert, Hinkle & Smith 1990) and variability of the color-indices and silicate features (Chan & Kwok 1988; Lloyd-Evans 1990) as well as a stringent requirement that primary and secondary must have very similar masses (Lambert et al. 1990). Near-infrared speckle interferometry as well as water maser monitoring also ruled out the presence of a luminous M-type companion to the primary carbon star (Engels & Leinert 1994) among silicate carbon stars.

Morris (1987) suggested that a binary system of a mass-losing red giant star and either a main-sequence dwarf or a white dwarf companion can develop an accretion disk around the companion, sometimes a circumbinary disk, and even a circum-primary disk, depending on the system configuration. Lloyd-Evans (1990) was inspired by Morris’s picture to propose that in silicate carbon stars the oxygen-rich material accumulated in a disk around a hypothetical companion when the primary was an oxygen-rich mass-losing star, which later turned into a carbon star through the third dredge-up. This picture reconciles the observed red infrared color and the relatively small extinction in the optical. The disk should be somewhat thickened and may extend to the circumbinary region to provide a sufficient mid-infrared flux. Engels & Leinert (1994) inferred for V778 Cyg and EU And a minimum radius of the molecular reservoir where water masers reside of $45 \sin i$ AU, where i denotes the inclination of the reservoir, which is 90° when seen edge-on, based on the assumed mass of $1 M_\odot$ for the primary, Keplerian motion for the maser components, and the constancy of radial velocities of the maser lines. Kahane et al. (1998) and Jura & Kahane (1999) proposed the existence of a circumbinary reservoir in Keplerian motion in silicate carbon stars, BM Gem and EU And, on the basis of the detection of CO J=1-0 and J=2-1 emission with very narrow widths at their systemic velocities. They suggested that the silicate grains reside in the

reservoir, which was presumably built by the influence of a postulated unseen companion when the primary was an oxygen-rich giant. Waters et al. (1998) noted the similarity to silicate carbon stars of Red Rectangle that possesses a circumbinary disk showing crystalline silicate features, an extended carbon-rich outflow, and narrow CO emission lines. However, Yamamura et al. (2000) suggested a picture similar to that reported by Lloyd-Evans (1990) based on analysis of the ISO spectrum of another silicate carbon star, V778 Cyg. They found that dust grains in the circumbinary region where the grains can be warm enough to emit the silicate features will be blown out in less than one orbital period, and thus unable to form a circumbinary reservoir. They concluded that the source of the silicate features must be the oxygen-rich material continuously blown out from the disk around a companion by the primary’s wind and radiation pressure.

The above scenarios all postulate a low-mass, low-luminosity companion, although no observational evidence has yet been provided. To gain further understanding of silicate carbon stars, it is essential to determine whether they indeed have a companion star. It would be very difficult, however, to detect a postulated low-luminosity companion in the optical or longer wavelength bands because the primary carbon star must outshine the companion by many orders of magnitude in these wavelength regions. In this respect, it has long been known that cool carbon stars exhibit extreme violet flux deficiency (Shane 1928), the agent of which has not yet been unambiguously identified (“violet opacity problem”). Indeed, cool carbon stars are very dim in the violet region; e.g., $U - V$ of the carbon star Y CVn is 8.9 (Nicolet 1978), while those of M5 giants and dwarfs are 4.2 and 2.8, respectively (Allen 1976). This phenomenon can be exploited to search for signatures of companions to silicate carbon stars in the violet spectral region. Therefore, we performed high sensitivity spectroscopic observations of the visually brightest silicate-carbon stars BM Gem, V778 Cyg, and EU And, in the violet spectral region. While we saw no significant violet emission in V778 Cyg or EU And, we have detected a featureless continuum below 4000 Å in BM Gem, where the Balmer continuum is higher than the Paschen continuum at the Balmer limit, which is very unusual for a cool luminous carbon star. In addition, the Balmer series lines were traced from H_γ up to H_{23} and they showed distinct P Cygni-type profiles. The profiles give a gas expansion velocity of at least 400 km s⁻¹. Such a high velocity outflow has never been observed in any type of currently mass-losing carbon star. Additional observations 75 days later further revealed considerable time variability of the Balmer lines. In addition, the BM Gem system was found to be similar to the Mira (*o* Cet) system, which is the prototype of a binary system consisting of a luminous AGB star (Mira A) and a low-mass, low-luminosity companion (Mira B). In the following sections, we discuss the origin of the continuum emission and the P Cygni-type Balmer lines, and argue for the presence of a companion to BM Gem.

2. OBSERVATIONS

Observations of BM Gem, the brightest silicate carbon star in the visual region, were made with the high dispersion spectrograph (HDS; Noguchi et al. 2002) at the Nasmyth focus of the Subaru telescope (Kaifu et al. 2000; Iye et al. 2004) on January 29 and April 14, 2001. We used the atmospheric dispersion corrector for the optical Nasmyth focus. The entrance slit width was set to $360\ \mu\text{m}$ ($0''.72$), which corresponded to a resolution of $\sim 50,000$. A quartz glass filter was inserted behind the slit. HDS is equipped with two mosaiced CCDs from EEV with 2048×4100 pixels of $13.5\ \mu\text{m}$ square. We used the $250\ \text{grooves mm}^{-1}$ cross-disperser grating to observe the range between $3550\text{--}5200\ \text{\AA}$ ($3550\text{--}4350\ \text{\AA}$ and $4400\text{--}5200\ \text{\AA}$). We made two 30-minute exposures and one 30-minute exposure in January and April, respectively. A bright J-type carbon star, Y CVn, was also observed for 15 minutes on February 1, 2001 (UT) with the same settings for comparison, because all the silicate carbon stars examined spectroscopically were known to be J-type stars (Lloyd-Evans 1990), which have low $^{12}\text{C}/^{13}\text{C}$ abundance ratios ($\lesssim 10$) in the atmosphere (Bouigue 1954). We also observed the second and third brightest silicate carbon stars, V778 Cyg and EU And, for 40 minutes each on July 30, 2001 with almost the same settings but we employed a slit width of $1''.0$ and 2×2 binning for the CCD readout to attain as high a signal to noise ratio as possible, which gave an effective spectral resolution of $\sim 38,000$. A summary of the observations is given in Table 1. The last column shows the signal to noise ratio at around $4000\ \text{\AA}$ in the reduced one-dimensional spectrum. The photometric and astrometric data of the targets taken from the literature are summarized in Table 2. The second and third columns show the Hipparcos parallax and the uncertainty in the parallax (ESA 1997), respectively. Near infrared data in the sixth through tenth columns are from Noguchi et al. (1981) for BM Gem and Y CVn and from Noguchi et al. (1990) for V778 Cyg and EU And. B and V magnitudes are from the Hipparcos and Tycho catalogs (ESA 1997) for BM Gem and Y CVn, and from Alksnis & Žaime(1993) for V778 Cyg and EU And. Data reduction was performed using the echelle package on NOAO IRAF². Standard procedures were followed: bias subtraction, flat fielding, scattered light subtraction, extraction of one-dimensional spectra, dispersion correction by Th-Ar lamp spectra, and removal of the echelle blaze profile by continuum lamp spectra. Strong cosmic ray events were removed manually.

We detected significant emission in BM Gem throughout the observed wavelength range. We then attempted to apply flux calibration to the observed spectra of BM Gem. A star, Feige 34, observed on January 28, 2001 under $\sim 0''.6$ seeing with $4''.0$ slit width to let virtually

² IRAF is distributed by the National Optical Astronomy Observatories, which is operated by the Association of Universities for Research in Astronomy, Inc. under cooperative agreement with the National Science Foundation

all the incident light enter the spectrograph, was used for our approximate flux calibration. We derived the system response from the observed spectra of the hot white dwarf Feige 34. We applied an atmospheric extinction correction based on the Mauna Kea extinction curve (Beland, Boulade & Davidge 1988) to the spectra, and compared them with the calibrated magnitudes at 50 Å interval of Feige 34 prepared in IRAF, which is based on Massey et al. (1988). We then corrected the spectra of BM Gem for the atmospheric extinction and the system response. Finally, we applied a correction for light losses from the entrance slit due to seeing. Seeing size was measured to be 0''.80' and 0''.85 for January and April observations, respectively. We approximated the seeing image by a single Gaussian and obtained values of 0.71 and 0.68 for the slit transmission efficiency for January and April, respectively, against 0''.72 slit width assuming perfect telescope guiding. The spectra of Y CVn were also calibrated in the same manner for comparison. The seeing size at the observation of Y CVn was 0''.80, which gave a slit efficiency of 0.71.

The uncertainty in the absolute flux densities thus obtained is non-negligible because the data were taken on different nights with somewhat different seeings with a slit width close to the size of the seeing image, a flux standard was observed on only one night, and the violet region is near the atmospheric cutoff, which is sensitive to extinction corrections. The uncertainty due to seeing and guiding, which applies to BM Gem, is estimated to be ± 0.25 mag in each spectrum, adopting maximum possible errors of 0''.2 in both seeing estimate and guiding. The uncertainty in the extinction correction which applies to both BM Gem and Feige 34 can give rise to an underestimate in their brightness of about 0.2 mag. It is obtained by assuming the employed extinction coefficient of $0.37 \text{ mag airmass}^{-1}$ at 3600 Å (Beland et al. 1988), with smaller values for longer wavelengths, was subject to a possible increase of 50%, although all our observations were made under clear sky conditions and the airmasses were only 1.01, 1.20, and 1.10 for BM Gem(Jan), BM Gem(Apr), and Feige 34, respectively. Taking all these uncertainties into account, each flux density derived is likely to be accompanied by an uncertainty range of $(-0.45, +0.25)$, while the relative uncertainty between BM Gem(Apr) and BM Gem(Jan) can be as large as $0.7(=0.25+0.25+0.2)$. Any difference between the two observations smaller than this magnitude is dominated by a calibration error and should be treated as insignificant.

We did not apply the above flux calibration to either V778 Cyg or EU And because we did not see any significant emission in the region shortward of 4000 Å. These stars are 3 magnitudes fainter than BM Gem in B (Table 2). If we put BM Gem farther away from us so that its B becomes 3 mag fainter, then any signal of the violet continuum on the raw CCD image becomes only one-quarter or less of the CCD read noise and merely equal to it or less even in the case of 2×2 binning. Then, the non-detection of the violet continua here in V778 Cyg and EU And indicates that they are not as bright as that of BM Gem

for their B magnitudes. Nevertheless, it does not necessarily mean that they do not have a similar violet continuum. It is necessary to achieve much higher sensitivities for V778 Cyg and EU And to distinguish between the presence and absence of a continuum like that in BM Gem. We will not discuss the violet spectra of V778 Cyg or EU And further in this paper.

The observed spectrum was corrected for the Doppler shift and transformed to the wavelength scale with respect to the local standard of rest (“LSR”) using the tasks RVCORRECT and DOPCOR in IRAF. The stellar systemic velocity with respect to LSR was also subtracted in the final spectra shown in this paper. Thus, matter stationary to the center of mass of the system should appear at zero velocity. We employed the systemic velocity of 73.2 km s^{-1} (V_{LSR}) for BM Gem based on mm-wave CO emission lines (Kahane et al. 1998; Jura & Kahane 1999). This is in agreement with V_{LSR} of 74.7 km s^{-1} derived from the heliocentric radial velocity of $85.3 \pm 0.4 \text{ km s}^{-1}$ obtained for the CO first overtone bands by Lambert et al. (1990). For Y CVn, we used 21.2 km s^{-1} , based on the mm-wave CO J=1-0 emission (Izumiura, Ukita, & Tsuji 1995), as the systemic velocity with respect to LSR. It should be noted that radial velocities of observed spectral lines given below will carry a typical uncertainty of $\sim 0.5 \text{ km s}^{-1}$ on the basis of the observed line widths and strengths, achieved S/N ratio, and employed spectral resolution.

3. RESULTS

3.1. Violet Spectra of BM Gem

The resulting spectra of BM Gem taken with the CCD that observes the shorter wavelength portion, reduced to a resolution of 1 \AA , are shown in Figure 1 along with those of Y CVn. We have adjusted the vertical scales so that the slopes of the spectra between 4050 \AA and 4200 \AA look similar to one another. The spectra of BM Gem show significant Balmer and Paschen continuum emission in the violet region, which is evident when compared with Y CVn, which shows no detectable violet continuum. What is more intriguing is that the level of the Balmer continuum is 1.3 times higher than that of the Paschen continuum when compared around the Balmer limit in both observation occasions. This indicates that the continuum emission comes from an ionized gas region. They also show a series of emission lines that are identified with Hydrogen Balmer series lines from H_γ through H_{23} . Moreover, the Balmer lines show P Cygni-type line profiles, suggesting the presence of an outflow being accelerated outward against the central continuum source. H_β emission was not identified at all in our spectra recorded on the CCD that covers the longer wavelength part, probably because the spectral range is dominated by the strong carbon star spectra. Broad Ca II K

emission with a blueward depression was also detected but Ca II H emission was absent. The Ca II H emission could be absorbed by the hydrogen in the outflow because the expected wavelength range of Ca II H line (3968.470 Å, Moore 1959) coincides with the absorption core of the P Cygni profile of H ϵ line (3970.074 Å, Moore 1959). Note here that the features that mimic emission lines, marked with small vertical ticks seen shortward of 4150 Å in Y CVn, are contaminations of ghost spectra of very strong red light of the star, probably due to the cross-disperser grating. The same ghost features are also present in the spectra of BM Gem at the same positions, by which only H₁₀ of the Balmer lines is significantly contaminated.

The fluxes per unit wavelength at wavelength λ , F_λ , of the Balmer continuum of BM Gem after the approximate flux calibration in §2 are 3.0×10^{-15} erg cm⁻² s⁻¹ Å⁻¹ in the January spectra and 4.3×10^{-15} erg cm⁻² s⁻¹ Å⁻¹ in the April spectra immediately shortward of the Balmer limit at 3646 Å. These correspond to 16.1 mag and 15.7 mag following the definition of $m \equiv -2.5 \log(F_\nu) - 48.59$, where m is the magnitude, ν is frequency, and F_ν is the flux per unit frequency at ν in erg cm⁻² s⁻¹ Hz⁻¹. Here, F_ν is calculated by $F_\nu = F_\lambda |d\lambda/d\nu| = c\nu^{-2}F_\lambda$ (i.e., $\nu F_\nu = \lambda F_\lambda$), where c is the speed of light. This definition gives 0.048 for the magnitude of Vega at 5556 Å (Hayes & Latham 1975). The apparent difference in the continuum level of 0.4 mag is not significant, considering the possible uncertainty of 0.7 mag given in §2. Thus, we argue that the continuum level is unchanged, and adopt a geometrical mean of the two values, 3.6×10^{-15} erg cm⁻² s⁻¹ Å⁻¹ or 15.9 mag. We take the differences of ± 0.2 mag between this 15.9 mag and the two direct values as an additional uncertainty. Adding this to that given in §2, the total uncertainty range has a magnitude of (-0.65, +0.45). Similarly, the Paschen continuum at 4000 Å has 16.2 mag and 15.6 mag in the January and April spectra, respectively, and they give 15.9 and (-0.75, +0.55) in magnitude as the flux level and uncertainty range, respectively. Note, however, that BM Gem shows light variation of 0.2–0.4 mag in 100 days in B and V bands (Alksnis & Žaime 1993). Whether BM Gem is indeed variable in the violet continuum is an interesting issue for future studies.

In the original high-resolution spectra of BM Gem, CN red system lines between 4830–5250 Å give average radial velocities around -1 km s⁻¹ with respect to the systemic velocity adopted in §2 in the two observations. Absorption features of Mn I triplet at 4030–4034 Å were identified, while low-excitation lines of Ti I were observed in emission shortward of 4040 Å, both of which are typical for late-N type carbon stars, as described by Gilra (1976). The Mn I lines at the two epochs give average radial velocities around -6 km s⁻¹, which are compatible with the mm wave CO outflow velocity of 7.5 km s⁻¹ and may suggest that they form in the mass-loss flow of the carbon star. The Ti I lines have apparent FWHMs of ~ 10 km s⁻¹ and show average radial velocities near 0 km s⁻¹ in the two observations,

suggesting that they originate in the extended atmosphere of the carbon star. The uncertainties in the average radial velocities given above are as large as 1 km s^{-1} for all of the CN red system, Mn I triplet, and Ti I lines. Whether this magnitude of uncertainties, which is slightly larger than the internal uncertainties of $\sim 0.5 \text{ km s}^{-1}$ given in §2, is due to their intrinsic variabilities or not is an issue for a future work. The continuum shortward of 4040 \AA is almost featureless except for the Balmer and Ti I lines. No absorption features typical of stellar photospheres are seen.

Figure 2 shows higher resolution views of the vicinity of H_δ , H_ϵ , and H_8 lines together with Ca II K line observed on the two nights 75 days apart. The zero systemic velocity corresponds to the middle of the P Cygni profile, which argues for the outflowing gas being associated with BM Gem. The line profiles show that the emitting gas, which is likely ionized, is expanding at a velocity as large as 400 km s^{-1} in the sight line. This is greater than the highest velocity outflows observed to date in AGB and post-AGB stars, V Hya (200 km s^{-1} , Knapp, Jorissen, & Young 1997), CRL 618 (200 km s^{-1} , Cernicharo et al. 1989), OH231.8+4.2 (330 km s^{-1} , Alcolea, Bujarrabal, & Sánchez Contreras 1996), and R Coronae Borealis stars ($200\text{--}350 \text{ km s}^{-1}$, Clayton, Geballe, & Bianchi 2003), with the exception of Mira B (250 and 400 km s^{-1} , Wood, Karovska, & Hack 2001, Wood, Karovska, & Raymond 2002) and V854 Cen (390 km s^{-1} , Clayton et al. 1993). It is, however, much smaller than those of jets seen in symbiotic objects (e.g., $\sim 6000 \text{ km s}^{-1}$ in MWC560, Tomov et al. 1990). In addition, a change in the line shape in each of the Balmer lines over a period of 75 days is evident. The blue edge of the absorption features shifted redward by 200 km s^{-1} , while the red edge did so by only 50 km s^{-1} .

3.2. Energetics of the Violet Emission

Our discoveries of the Balmer and Paschen continua, the former being higher than the latter, the P Cygni-type Balmer series lines, and their line profile variability all suggest that BM Gem is associated with a compact ionized gas region that is accelerated to form a rather spherical, high velocity outflow. No mechanism is known for a single cool luminous carbon star to produce an ionized gas region as well as a high velocity outflow. They can, however, be accounted for if we introduce an unseen, low-mass companion that captures matter in the stellar wind from the primary to give rise to an accretion disk. This hypothesis is partially supported by similar spectral features observed in Mira B (*o* Cet B) (see §4), which is a low-mass companion to the AGB star Mira A (*o* Cet A) and is considered to be associated with an accretion disk (Joy 1926, 1954; Deutsch 1958; Warner 1972; Reimers & Cassatella 1985). Low-mass companions with an accretion disk have also been suggested for R Coronae

Borealis stars, which show outflows with similar high velocities and He I lines that require excitation sources (Rao et al. 1993; Clayton et al. 2003).

Formation of an accretion disk has proven to be robust around a companion star to a mass-losing giant in various detached configurations (Mastrodemos & Morris 1998, 1999). The inner part of the accretion disk must be heated by the released gravitational potential energy from the accreting matter. A hot ionized gas region should form between the innermost region of the disk and the surface of the companion. The accretion phenomenon may also be responsible for the discovered high velocity, variable outflow, although the details of the acceleration mechanism is not yet settled for this type of outflow. Alternatively, the outflow may be due to dust formation in the circumcompanion region, analogous to the scenario proposed for RCB stars by Clayton (1996). Dust grains would be accelerated through radiation pressure, dragging gas to form the observed high velocity outflow. The ionization could then be due to collisional ionization in the flow. In this case, to be compatible with the observed broad absorption core that extends from the systemic velocity to the terminal velocity in the P Cygni profile, the ionization must occur before the gas acceleration is completed. Otherwise the absorber in front of the continuum source has terminal outflow velocity and a much narrower absorption component appears near the terminal velocity. In either case of an outflow powered by accretion or driven by radiation pressure on dust grains, the observed spectral features favor the presence of a companion to BM Gem.

The companion should be either a white dwarf or a low-mass dwarf star because hypotheses invoking a luminous companion have been rejected by previous studies (Noguchi et al. 1990; Lambert et al. 1990; Chan & Kwok 1988; Lloyd-Evans 1990). The gas expansion velocity provides a hint to distinguish the candidates for the companion. White dwarfs have escape velocities on the order of several thousand km s^{-1} , while those of low-mass dwarf stars are of the order of several hundred km s^{-1} . If gas acceleration occurs near the surface of the secondary and the flow is aligned with the sight line, the latter is the case for BM Gem. However, the former could also be the case if the acceleration takes place at some point distant from the white dwarf, as suggested by Warner (1972), or the flow has a narrow opening angle and is markedly inclined with respect to the sight line. Below, we examine whether such a binary and accretion hypothesis is plausible energetically.

We first attempted to determine the absolute magnitudes of BM Gem at the observed wavelengths by finding the distance to BM Gem. Although it exists, the Hipparcos parallax of BM Gem (Table 2) is unreliable. Claussen et al. (1987) gave 1.51 kpc assuming that carbon stars have a constant absolute K-band magnitude of -8.1. We made another estimate by comparing the near-infrared flux densities of BM Gem with those of Y CVn, as they are ^{13}C -rich (J-type) carbon stars resembling each other in the spectral characteristics in the

optical and near-infrared (Barnbaum 1991; Ohnaka & Tsuji 1999, Yamamura et al. 2000), which may indicate they have similar intrinsic properties. Y CVn is the only J-type star that has a relatively reliable Hipparcos parallax (Table 2) of 218 pc with 16% uncertainty. It is evident from the data shown in Table 2 that the differences between Y CVn and BM Gem in I through L bands are quite constant with a simple mean of 3.72, which indeed shows the two stars to be similar and gives a distance to BM Gem of 1.21 kpc. In addition, the distance of 1.51 kpc reported by Calussen et al. may be reduced to 1.14 kpc, considering the distance they gave of 0.29 kpc for Y CVn should be readjusted to 0.218 kpc. Hence, we adopted 1.2 kpc with a conservative uncertainty factor of 1.2 as a reasonable estimate for the distance to BM Gem. The total luminosity then becomes $5.4 \times 10^3 L_{\odot}$ (cf. Groenewegen et al. 1992), which implies that they are on the AGB even with the distance uncertainty.

Interstellar extinction toward BM Gem ($l = 193^{\circ}.2$ and $b = 17^{\circ}.2$) at 3650 Å (= U band), A_{3650} , is estimated to be at most 0.6 mag. It is obtained by

$$A_{3650} = \alpha N(HI)(N(H)/E(B - V))^{-1}(A_V/E(B - V))(A_{3650}/A_V), \quad (1)$$

where $N(HI)$ is the column density of atomic neutral hydrogen, α is a conversion factor from $N(HI)$ to the total column density of neutral hydrogen $N(H)$ including H I and H₂, $E(B - V) = A_B - A_V$, and A_B and A_V are the extinction at B band and V band, respectively. We read $N(HI) = 7 \times 10^{20}$ atoms cm⁻² in the direction of BM Gem from Heiles (1975). Other quantities are found in Cox (2000) and references therein: $N(H)/E(B - V) = 5.8 \times 10^{21}$ atoms cm⁻² mag⁻¹ (Bohlin, Savage, & Drake 1978); $R_V = A(V)/E(B - V) = 3.1$, a standard value for diffuse interstellar matter; $A_{3650}/A_V = 1.56$ for $R_V = 3.1$ (Cardelli, Clayton, & Mathis 1989). Then, we find $A_{3650} = 0.6\alpha$, which should be an upper limit because the column density that Heiles (1975) gave is an upper limit to BM Gem, which lies somewhere between the boundary of the HI gas distribution in that direction and us. Since there are no significant molecular clouds found in the direction of BM Gem (e.g., Dame, Hartmann, & Thaddeus 2001), α should be close to unity and the use of $R_V = 3.1$ should be justified. Therefore we regard $A_{3650} = 0.6$ as an upper limit. We have also obtained another estimate of $A_{3650} = 0.3$ for the interstellar extinction toward BM Gem, using $E(B - V) = 0.067$ read from Schlegel, Finkbeiner, & Davis (1998) by way of NASA/IPAC Infrared Science Archive, $R_V = 3.1$, and $A_{3650}/A_V = 1.56$. This is another upper limit because BM Gem must lie somewhere between the boundary of the dust distribution in the sight line and us. Taking these into account we adopt the 0.3 mag directly from far-infrared dust observations as a nominal value, the 0.6 mag from the H I observations as a maximum value, and no extinction as a minimum value, for A_{3650} to BM Gem, namely, $A_{3650} = 0.3 \pm 0.3$. Then we find the absolute magnitudes at U (M_U) and 4000 Å (M_{4000}) to be $5.2^{+1.0}_{-1.2}$ and $5.2^{+1.1}_{-1.3}$, respectively. These are obtained from the observed magnitudes of $M_U = 15.9^{+0.45}_{-0.65}$ and $M_{4000} = 15.9^{+0.55}_{-0.75}$, the adopted distance of 1.2 kpc, its uncertainty factor

of 1.2, and the same interstellar extinction correction of -0.3 ± 0.3 mag to both of them. The distance and uncertainty factor corresponds to -10.4 ± 0.2 mag.

The violet continuum is not simply explained by the photosphere of a postulated companion. For the case of a dwarf companion, the probable range of M_{4000} between +6.3 and +3.9 corresponds to a photosphere with a spectral type between late G and late F, which should show numerous strong absorption lines in the violet region. The violet continuum of BM Gem is, however, featureless except for the Ti I emission lines due to the primary carbon star and the Balmer series lines due to the outflow, as mentioned in section 3.1. The featureless continuum requires that the companion's photosphere is smeared by veiling with/without obscuration and contributes only a small fraction of the observed violet continuum. Considering the S/N ratios in the original high-resolution spectra of ~ 15 , we should be able to detect absorption lines of which central depths are as weak as 20% of the continuum level at 3σ confidence. In this violet region, there are many absorption lines the central depths of which are as strong as 80% of the continuum level in late F through late K dwarfs. For such strong lines to appear weaker than the 3σ upper limit of 20%, the veiling should be at least 4 times the companion's photosphere. Possible cases are an F- or G-type dwarf obscured by continuous absorption and covered with veiling and a dwarf later than G-type either obscured or not by continuous absorption and covered with veiling. Obscured B- or A-type photosphere is not plausible for the violet continuum because we do not see the Balmer Jump typical for such spectral types and because the companion should be less massive than the primary carbon star. The observed violet continuum also cannot be explained by the photosphere of a white dwarf companion, because the U band brightness, M_U , of a DB white dwarf with effective temperature of 25000 K is 9.1 (Allen 1976), and those classified as DA and later are less luminous. Therefore, most of the observed violet flux in BM Gem should have an origin other than the photosphere of the assumed companion, which is consistent with our accretion hypothesis.

The total flux of the observed continuum emission $F^{cont} = \int_0^\infty F_\nu^{cont} d\nu$ is approximately obtained by $\nu_0 F_{\nu_0}^{cont}$, where ν and F_ν^{cont} mean frequency and the flux of the continuum at ν per unit frequency range (flux density) and $F_{\nu_0}^{cont}$ and ν_0 are their typical values. We adopt the frequency at $Ly\ \alpha$ (1216 Å), $\nu_{Ly\alpha}$ for ν_0 and the flux density at $\nu_{Ly\alpha}$, $F_{\nu_{Ly\alpha}}^{cont}$ for $F_{\nu_0}^{cont}$ to obtain $F^{cont} \sim \nu_{Ly\alpha} F_{\nu_{Ly\alpha}}^{cont} = \lambda_{Ly\alpha} F_{\lambda_{Ly\alpha}}^{cont}$, where $\lambda_{Ly\alpha}$ is the wavelength of $Ly\ \alpha$ and $F_{\lambda_{Ly\alpha}}^{cont}$ is the flux of the continuum per unit wavelength range at $Ly\ \alpha$ wavelength. Here, we assume $F_{\lambda_{Ly\alpha}}^{cont}$ is approximated by $F_{\lambda_{BL}^-}^{cont}$, which is the flux of the continuum per unit wavelength range immediately shortward of the Balmer limit at 3646 Å, for which we obtained 3.6×10^{-15} erg cm $^{-2}$ s $^{-1}$ Å $^{-1}$ in §3.1. These approximations should be valid because model spectra of ionized gas show that the continuum emission diminishes rapidly toward higher frequencies with respect to $Ly\ \alpha$ line and because the level of the continuum flux per

unit wavelength from an ionized gas at $Ly\ \alpha$ wavelength is similar to that just shortward in wavelength of the Balmer limit (e.g., Harrington, Lutz, & Seaton 1981; Pottasch et al. 1981). Then, the product $\nu_{Ly\alpha} F_{\nu_{Ly\alpha}}^{cont}$ should give a reasonable estimate of the total flux. The above approximations, however, may overestimate the total flux, and another uncertainty of $(-0, +1)$ in magnitude should be added.

Now, assuming spherical symmetry of the radiation field, the gas radiative luminosity, L_g , can be estimated as

$$L_g \simeq 4\pi D^2 \nu_{Ly\alpha} F_{\nu_{Ly\alpha}}^{cont} = 8 \times 10^{32} \text{ erg s}^{-1} \sim 0.2 L_{\odot}, \quad (2)$$

where D denotes the distance to BM Gem. The total uncertainty range has a magnitude of $(-1.2, +2.0)$ by summing those discussed previously, or $0.03\text{--}0.6 L_{\odot}$. L_g in this range is always larger than the gas kinematic luminosity, $(1/2) \dot{m}_{out} V_e^2$, and thermal luminosity, $(3/2)nkT4\pi R^2 V_e$, and dominates the total luminosity as far as $\dot{m}_{out} \leq 10^{-9} M_{\odot} \text{ yr}^{-1}$ and $T \leq 10^6$ K. Here, \dot{m}_{out} , V_e , and n are the mass ejection rate, outflow velocity, and total particle number density, respectively, of the high velocity outflow. k , T , and R are the Boltzmann constant, temperature of the gas, and radius under consideration from the center of the outflow source, respectively.

Maximum energy input, L_a , expected from the mass-accretion by a companion, is constrained by the gravitational potential energy release from the accreting matter, i.e.,

$$L_a = G(M_2 \dot{M}_2)/r = 0.16 (M_2/0.5)(\dot{M}_2/10^{-10})(r/0.01)^{-1} L_{\odot}, \quad (3)$$

where G , \dot{M}_2 , M_2 , and r are the gravitational constant, the companion's mass accretion rate in $M_{\odot} \text{ yr}^{-1}$, its mass in M_{\odot} , and its radius in R_{\odot} , respectively. In this equation M_2/r is almost constant and near unity for dwarf stars of type late F to late K, and is 20–70 for white dwarfs (Allen 1976). For a white dwarf of $0.5 M_{\odot}$ with $0.01 R_{\odot}$ (Allen 1976), an accretion rate of $(0.2 - 4) \times 10^{-10} M_{\odot} \text{ yr}^{-1}$ can afford the observed continuum luminosity of $(0.03 - 0.6) L_{\odot}$, whereas a K5 dwarf of $0.69 M_{\odot}$ and $0.74 R_{\odot}$ (Allen 1976) can give rise to the observed luminosity when the mass accretion rate is $(0.1 - 2) \times 10^{-8} M_{\odot} \text{ yr}^{-1}$. It is not self-evident if the latter accretion rate is feasible for a dwarf companion in a binary system compatible with the observations, given the current mass loss rate of $3 \times 10^{-7} M_{\odot} \text{ yr}^{-1}$ in BM Gem (Kahane et al. 1998).

According to Warner (1972), the Bondi-Hoyle type mass accretion rate is written as

$$\begin{aligned} \dot{M}_2 &= (1/2)G^2 \dot{M}_1 M_2^2 [(v_{rel}^2 + c^2)^{3/2} v_e]^{-1} d^{-2} \\ &= 3.4 \times 10^{-9} (\dot{M}_1/10^{-7}) (M_2/0.5)^2 [(v_{rel}^2 + c^2)^{3/2} v_e / (7.5)^4]^{-1} (d/30)^{-2} M_{\odot} \text{ yr}^{-1}, \end{aligned} \quad (4)$$

where v_e , v_{rel} , and c are the mass outflow velocity from the primary carbon star, relative velocity of the companion to the primary outflow, and speed of sound of the material,

respectively, all in km s^{-1} , and \dot{M}_1 and d are the mass loss rate of the primary in $M_\odot \text{ yr}^{-1}$ and binary separation in AU, respectively. Substituting equation (4) in equation (3) we find,

$$\begin{aligned} L_a &= (1/2)G^3\dot{M}_1M_2^3[(v_{rel}^2 + c^2)^{3/2}v_e r d^2]^{-1} \\ &= 5.2 (\dot{M}_1/10^{-7}) (M_2/0.5)^3 [(v_{rel}^2 + c^2)^{3/2}v_e/(7.5)^4]^{-1} (d/30)^{-2} (r/0.01)^{-1} L_\odot. \end{aligned} \quad (5)$$

The speed of sound of the material can be neglected here as it is likely that the wind is flowing supersonically. Here, we may write $v_{rel} = (v_e^2 + v_{orbit}^2)^{1/2}$, where v_{orbit} is the orbital velocity of the companion (Warner 1972; Jura & Helfand 1984).

If we assume BM Gem is in a binary system consisting of a carbon star of $1.5 M_\odot$ (Claussen et al. 1987; Groenewegen et al. 1992) and a dwarf of $0.5 M_\odot$, in a circular orbit with a separation of 30 AU, which is one likely configuration, then the orbital velocity of the companion about the primary becomes 7.7 km s^{-1} . The outflow velocity of the primary carbon star is 7.5 km s^{-1} and the current mass loss rate is $\sim 3 \times 10^{-7} M_\odot \text{ yr}^{-1}$ in BM Gem (Kahane et al. 1998). Then, equation (5) gives an accretion luminosity of $0.08 L_\odot$, which is at least compatible with the observed luminosity of BM Gem when its uncertainty range is taken into account. In their smoothed particle hydrodynamic calculations, Mastrodemos & Morris (1999) found that the Bondi-Hoyle accretion is not as efficient as initially thought. The obtained efficiency (\dot{M}_2/\dot{M}_1) spreads over a range between 0.1% and 10% for the cases they examined that are compatible with the configurations under consideration here. The efficiencies they found differ not by an order but by a factor from those obtained using equation (4) for the same parameter sets. A dwarf companion is thus at least compatible with the observations.

4. DISCUSSION

In the previous section, we showed that our results were compatible with BM Gem being accompanied by a low-mass, low-luminosity companion with an accretion disk, for which both a main-sequence star and a white dwarf are viable. In this section, we further consider the characteristics of the BM Gem system.

The observed UV-optical (violet) spectral features of BM Gem nearly parallel those of Mira (*o* Cet). Mira is known to consist of a long period variable on the asymptotic giant branch, Mira A and a low-mass, low-luminosity companion separated by about $0''.6$ (~ 70 AU), Mira B (Karovska et al. 1997 and references therein). Joy (1926, 1954) reported the first detection of a UV-optical continuum and of complex profiles of Hydrogen Balmer lines with emission and absorption cores in Mira B. Figure 8 of Reimers & Cassatella (1985) showed that both Balmer and Paschen continua existed, and the level of the former was higher than

that of the latter. The Balmer lines were found to be in P Cygni-type and their profiles were shown to be highly variable on a time scale similar to that found for BM Gem (Joy 1926, Yamashita & Maehara 1977), although the lines were not in P Cygni-type in Reimers & Cassatella (1985). The P Cygni profiles indicated that the outflow velocity was as large as 400 km s^{-1} (Wood et al. 2002). Warner (1972) examined the energetics of Mira B and reported that its total luminosity of $\sim 0.2 L_{\odot}$ could be accommodated by the Bondi-Hoyle type accretion of Mira A's wind to Mira B, if the mass loss rate from Mira A is greater than $0.8 \times 10^{-7} M_{\odot} \text{ yr}^{-1}$. The actual mass loss rate of Mira A is $\sim 3 \times 10^{-7} M_{\odot} \text{ yr}^{-1}$ (Ryde & Schöier 2001), which supports the Bondi-Hoyle type accretion. Jura & Helfand (1984) also found the UV-optical luminosity of Mira B to be $0.2 (0.05\text{--}1) L_{\odot}$. The above parallels between BM Gem and Mira in the spectral features as well as the UV-optical luminosity support the presence of a companion to BM Gem.

Based on the X-ray luminosity as well as of the outflow velocity of $\sim 400 \text{ km s}^{-1}$, the companion of BM Gem may not be a white dwarf but a dwarf. Here, we again present a parallel discussion with Mira. A very low X-ray luminosity, which is $\sim 10^{-3}$ of the UV-optical luminosity, in the Mira system led Jura & Helfand (1984) to conclude that Mira B was not a white dwarf but a dwarf. They argued that the X-ray luminosity would be comparable to the UV-optical luminosity if the companion was a white dwarf. Reimers & Cassatella (1985) noted that there was no direct evidence for the presence of a hot white dwarf companion to Mira A, although they favored a white dwarf companion. Based on a similar discussion, Ireland et al. (2007) recently concluded that Mira B is a K5 dwarf of $0.7 M_{\odot}$. If Mira B is indeed a dwarf, then the X-ray luminosity of BM Gem would be as small as that of Mira in the case of a dwarf companion but could be 10^3 times as much for a white dwarf companion. Mira has an X-ray photon flux of $7.6 \times 10^{-3} \text{ counts s}^{-1}$ in the 0.1–2.4 keV energy band in the second ROSAT source catalog of pointed observations (ROSAT Consortium 2000). The X-ray flux from BM Gem in the same energy band could be as much as $\sim 0.08 \text{ counts s}^{-1}$ for a white dwarf companion, with the difference in their distances of a factor 10 taken into account. It should have been detected in the ROSAT all-sky survey (Voges et al. 1999, 2000), the detection limit of which was about $0.05 \text{ counts s}^{-1}$, which is actually not the case. This argues for a dwarf as the companion of BM Gem. However, that both Mira and BM Gem possess a white dwarf companion cannot be excluded completely, because there may exist a mechanism that suppresses the X-ray luminosity arising from the accretion process and one to accelerate the outflow from some distant point from the white dwarf simultaneously. The latter mechanism is favorable for the picture suggested for Mira B by Warner (1972). It is thus difficult to choose exclusively between a dwarf and a white dwarf as the companion, although the data favor a dwarf.

The binary separation of the BM Gem system is only loosely constrained. The separation

is found to be $(6-0.3) \times 10^1$ AU for a dwarf companion, while that for a white dwarf companion is $(5-1) \times 10^2$ AU to reproduce the observed luminosity of $0.03-0.6 L_\odot$ using equation (5). We adopted $\dot{M}_1 = 3 \times 10^{-7}$ and $v_e = 7.5$ and assumed that M_1 (the mass of the primary in M_\odot) = 1.5, $M_2 = 0.5$, $r=0.65$ (dwarf) or 0.016 (white dwarf), and the system is in a circular orbit. Further, for any combination of M_1 between 1.0 and 2.0 and M_2 between 0.3 and 1.2 but $M_1 > M_2$ (dwarf) or between 0.3 and 0.7 (white dwarf), there are upper limits of 210 AU and 930 AU for a dwarf and a white dwarf companion, respectively, where realistic r corresponding to M_2 (Allen 1976, Lang 1999) is used. As equation (3) gives an upper limit and equation (4) is suspected to overestimate the accretion rate (Mastrodemos & Morris 1999), the derived upper limits for the separation are relatively stringent. Mastrodemos & Morris (1999) and Soker & Rappaport (2000) suggested from theoretical considerations that the separation should be $\lesssim 30$ AU to form an accretion disk around a companion, irrespective of whether it is a dwarf or a white dwarf, in the detached binary configurations under consideration here. The observation that Mira B, which is at least 70 AU from Mira A, is associated with an accretion disk despite the moderate mass loss rate of Mira A of $\sim 3 \times 10^{-7} M_\odot \text{ yr}^{-1}$ suggests that the current hydrodynamic simulations do not constrain the upper-limit of the separation very well. As BM Gem has been shown to be a system resembling Mira, its binary separation could be as large as 70 AU. Ohnaka et al. (2006) derived an upper limit of $\sim 60-80$ AU for the diameter of the inner dust-free region in the silicate carbon star IRAS08002-3803 from mid-infrared interferometry, which at the same time gives an upper limit for the postulated binary separation of ~ 80 AU. However, they suggested that silicate carbon stars with an optically thin dust reservoir, to which BM Gem belongs, have binary separations wider than those of silicate carbon stars with an optically thick reservoir, to which IRAS08002-3803 belongs. In addition, if we pose a constraint that we do not see a Roche-Lobe overflow, then we find the binary separation should be larger than 1.8 AU for any combination of mass ratio between 1 and 7 and carbon star radius between 1 and 1.5 AU using the formulation by Paczyński (1971).

Luminosity of the silicate dust in BM Gem, L_d is estimated as

$$L_d = 4\pi D^2 \int F_\nu^{\text{silicate}} d\nu \sim 4\pi D^2 (1/5) \nu_{9.7\mu\text{m}} F_{\nu_{9.7\mu\text{m}}}^{\text{silicate}} = 4 \times 10^{35} \text{ erg s}^{-1}, \quad (6)$$

where F_ν^{silicate} , $\nu_{9.7\mu\text{m}}$, and $F_{\nu_{9.7\mu\text{m}}}^{\text{silicate}}$ are the flux density due to silicate dust, frequency at $9.7 \mu\text{m}$, and flux density due to silicate dust at $9.7 \mu\text{m}$ peak, respectively. We assume the emission is isotropic, the feature extends over $8-12 \mu\text{m}$, and has a flux density of about $1.2 \times 10^{-11} \text{ W m}^{-2}$ at the peak, which is read from the “IRAS Low Resolution Spectrograph” atlas (Joint IRAS Science Working Group 1986). The factor $1/5$ is a roughly determined correction factor for substituting the integration with the multiplication obtained by a simple calculation of $(1/2)(12 \mu\text{m}-8 \mu\text{m})/(9.7 \mu\text{m})$. The dust luminosity is then $\sim 110 L_\odot$. The

accretion process discussed here cannot be the energy source of the silicate emission lines. The energy must be supplied by the radiation from the primary carbon star of $\sim 5 \times 10^3 L_{\odot}$ (see §3.2). The dust luminosity indicates that about 2% of the total stellar luminosity is captured by the dust grains responsible for the silicate features. Barnbaum et al. (1991) found similar values of 1–2 % in BM Gem and V778 Cyg.

Silicate emission features have been speculated to arise from a circumstellar disk around a companion as well as from a thickened circumbinary disk (Lloyd-Evans 1990). Engels & Leinert (1994) inferred a minimum radius for a circumbinary molecular reservoir of $45 \sin i$ AU, where i denotes the inclination of the reservoir, which is 90° when seen edge-on, for V778 Cyg and EU And, assuming a $1 M_{\odot}$ primary and circular Keplerian motion of the reservoir. They based their inference on constancy better than $0.06 \text{ km s}^{-1} \text{ yr}^{-1}$ of the radial velocity of the water maser lines. Kahane et al. (1998) and Jura & Kahane (1999) detected a very narrow emission component in the mm-wave CO lines in BM Gem and EU And. They interpreted the narrow component as due to a circumbinary reservoir in Keplerian motion formed by some binary interaction with an unseen companion. They argue that the oxygen-rich material responsible for the silicate emission is stored in the long-lived circumbinary reservoir of 100–1000 AU size, which was formed when the primary star was an oxygen-rich mass-losing star. This picture is further reinforced by the study of Red Rectangle by Waters et al. (1998) who noted the similarity to silicate carbon stars of Red Rectangle, which possesses a circumbinary disk showing crystalline silicate features, an extended carbon-rich outflow, and narrow CO emission lines. The circumbinary reservoir of 100–1000 AU size is compatible with both the binary separation of $(0.3\text{--}6) \times 10^1$ AU (as well as a stringent upper limit of 210 AU) derived for a dwarf companion to BM Gem and the separation of $(1\text{--}5) \times 10^2$ AU (as well as a stringent upper limit of 930 AU) for a white dwarf companion.

However, Yamamura et al. (2000) found that silicate dust grains responsible for the emission features in V778 Cyg should have temperature between 600 and 300 K, which implies their location to be between about 25 and 100 AU (12–50 stellar radii) from the primary. They concluded that a circumstellar disk around an invisible companion should be the reservoir of oxygen-rich material, because they found it difficult to locate a circumbinary disk in the vicinity of the companion’s orbit. Dust grains there will be swept outward in less than one orbital period by radiation pressure from the primary. They speculated that the silicate features originate from oxygen-rich material continuously blown out by radiation pressure of the primary from the circumcompanion disk that was built when the primary was an oxygen-rich mass-losing star. Furthermore, Ohnaka et al. (2006) suggested that silicate carbon stars may be classified into two groups: one with an optically thick circumbinary dust reservoir with a smaller binary separation, and another with an optically thin dust outflow from the companion’s disk with a wider binary separation. Following their criteria,

BM Gem belongs to the latter group, and thus may show dust outflow from the companion, possibly extending out in a region at 50–100 AU from the primary. Therefore, the region at 30–100 AU is a likely location of the circumstellar molecular/dust reservoir according to both Yamamura et al. and Ohnaka et al. This location is compatible with the binary separation for a dwarf companion, but not with the separation for a white dwarf companion.

Finally, it should be noted that all of the silicate carbon stars examined spectroscopically are known to be J-type stars (Lloyd-Evans 1990, 1991), while the opposite is not true. It has been argued that J-type carbon stars are the direct descendants of R-type carbon stars (Lloyd-Evans 1990; Lambert et al. 1990), which form through a mechanism unrelated to the third dredge-up, as both groups of stars are ^{13}C -rich and lack s-process enhancements in the surface chemical compositions (Utsumi 1985, Dominy 1985). Abia & Isern (2000), however, favor another scenario in which the low-mass J-type stars discussed here form via a combination of non-standard extra mixing and cool bottom processing (Wasserburg, Boothroyd, & Sackmann 1995) early on the AGB, which is consistent with their luminosities being similar to those of normal cool carbon stars on the AGB (Wallerstein & Knapp 1998; Alksnis et al. 1998). As there seems to be a connection between the J-type nature and the silicate features, the presence of a companion to BM Gem would suggest a possible connection between binarity and J-type phenomena, which is worth investigating further. Radial velocity monitoring of J-type stars would be important, which could be carried out by observing the Ti I emission lines in the violet region as well as numerous photospheric molecular absorption lines.

5. CONCLUSIONS

We observed the violet spectra of the three brightest silicate carbon stars, BM Gem, V778 Cyg, and EU And, using the High Dispersion Spectrograph on the Subaru telescope, and used a prototypical J-type carbon star Y CVn for comparison. Balmer continuum and Paschen continuum emission typical for ionized gas were found to be prominent in the region shortward of 4000 Å in BM Gem, while no significant emission was observed in the same region in V778 Cyg, EU And, or Y CVn. In BM Gem, Balmer series lines were also detected from H_γ through H_{23} , and they showed P Cygni-type line profiles. Broad Ca II K emission with blueward depression was also found, while the Ca II H line is missing perhaps because it is absorbed by hydrogen in the outflow. The P Cygni profiles give the gas outflow velocity of at least 400 km s $^{-1}$. Such spectral features have not been observed in other cool luminous carbon stars. Furthermore, the P Cygni profiles changed significantly within a period of 75 days, suggesting a compact geometry of the outflow. The overall spectral features mimic

those of Mira B. All these features in the cool carbon star BM Gem suggest the presence of a companion that gives rise to an accretion disk, which is responsible for the ionized gas region and the observed high velocity outflow.

We investigated the energetics of the observed emission assuming a binary system and Bondi-Hoyle type mass accretion process. The luminosity of the observed continuum emission is estimated to be ~ 0.2 (0.03–0.6) L_{\odot} , while the silicate dust features convey about 110 L_{\odot} , which shows that the silicate dust grains are heated not by the phenomenon discovered here but by radiation from the carbon star. We found that the violet continuum luminosity is accommodated if an accretion rate on the order of $10^{-8} M_{\odot} \text{ yr}^{-1}$ is achieved to a dwarf companion, while $10^{-10} M_{\odot} \text{ yr}^{-1}$ is sufficient to a white dwarf companion. Although the required accretion efficiency seems rather high, a main-sequence companion is favored based on the observed outflow velocity of 400 km s^{-1} and the non-detection of X-ray flux in the ROSAT all sky survey. The possibility of a white dwarf companion, however, cannot be ruled out, because the outflow could be narrow and inclined with respect to the sight line or be accelerated at some distant point from the surface of the white dwarf.

Based on the above findings combined with those of previous studies, we conclude that BM Gem is associated with a low-mass, low-luminosity companion giving rise to an accretion disk. We note that the spectral features and UV-optical luminosity obtained for the BM Gem system closely resemble those of the Mira system, which should represent the actual similarity between the binary configurations of the two systems. We derived the binary separations based on the observed UV-optical luminosity as $(0.3\text{--}6) \times 10^1 \text{ AU}$ and $(1\text{--}5) \times 10^2 \text{ AU}$ for a dwarf and a white dwarf companion, respectively, assuming the primary mass of $1.5 M_{\odot}$, companion mass of $0.5 M_{\odot}$, circular orbits, and Bondi-Hoyle type accretion. We also derived another stringent upper limit of the separation of 210 AU and 930 AU for a dwarf and a white dwarf companion, respectively. The separations for a dwarf are compatible with both the circumcompanion dust reservoir proposed by Yamamura et al. (2000) and Ohnaka et al. (2006) and the circumbinary dust reservoir proposed by Kahane et al. (1998) and Jura & Kahane (1999), while those for a white dwarf are plausible only for the circumbinary reservoir. However, it is still difficult to choose between the two scenarios for the dust reservoir responsible for the silicate emission features in BM Gem. A very high angular resolution imaging in the ultraviolet would be interesting to depict the reservoir through the violet continuum emission scattered by the silicate grains. If the silicates are located in a circumbinary reservoir, we will see a ring-like structure, while we may see a spiral structure if they are blown out continuously from a circumcompanion disk. It is also important to carry out high sensitivity, medium resolution spectroscopy in the ultraviolet of silicate carbon stars other than BM Gem to determine whether the violet spectral features are common among silicate carbon stars. Theoretical studies of the formation mechanism of the dust reservoir

are also required.

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Table 1. Observation Summary

Name	RA(h m s) (J2000)	Dec($^{\circ}$ ' ") (J2000)	Exp (sec)	Res. ($\lambda/\Delta\lambda$)	Date (UT)	S/N (@4000 Å)
BM Gem	07 20 58.9	+25 00 07.28	3600	50,000	2001 Jan 29	~ 15
			1800	50,000	2001 Apr 14	~ 15
V778 Cyg	20 36 07.4	+60 05 26.2	2400	38,000	2001 Jul 30	< 1
EU And	23 19 58.2	+47 14 28	2400	38,000	2001 Jul 30	< 1
Y CVn	12 45 07.8	+45 26 24.9	900	50,000	2001 Feb 1	~ 1
Feige 34	10 39 36.7	+43 06 09.3	300	9,000	2001 Jan 28	~ 80

Table 2. Astrometric and Photometric Data

Name	π (mas)	σ_{π} (mas)	B	V	I	J	H	K	L
BM Gem	1.83	1.24	10.72	8.40	4.96	4.28	3.32	2.75	2.47
V778 Cyg	13.75	10.26	...	5.25	4.20	3.54	3.18
EU And	13.70	10.47	...	5.41	4.37	3.79	3.33
Y CVn	4.59	0.73	8.41	5.42	1.25	0.59	-0.37	-0.89	-1.42

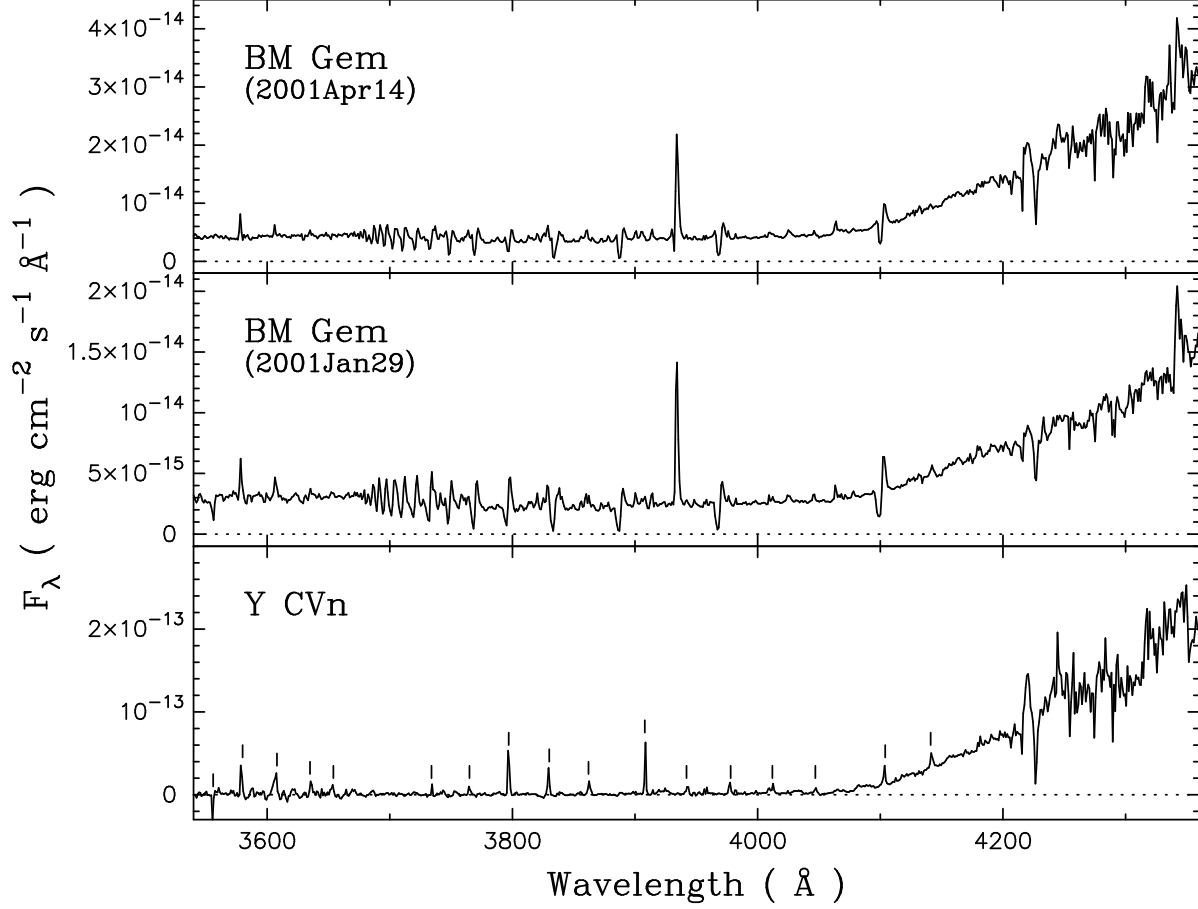


Fig. 1.— Violet spectra of a silicate carbon star, BM Gem, on January 29 and April 14, 2001, and a prototypical J-type carbon star, Y CVn. All the spectra are binned to 1 \AA step. The dotted horizontal line indicates the zero level. Note the significant continuum emission, Balmer lines, and Ca II K emission in BM Gem. The small difference in the continuum level is probably due to the measurement uncertainty (see text for details). Small vertical ticks in the panel of Y CVn give the positions of artifacts due to strong red light contamination, which is also present in BM Gem but is not prominent because of the strong continuum (see text for details)

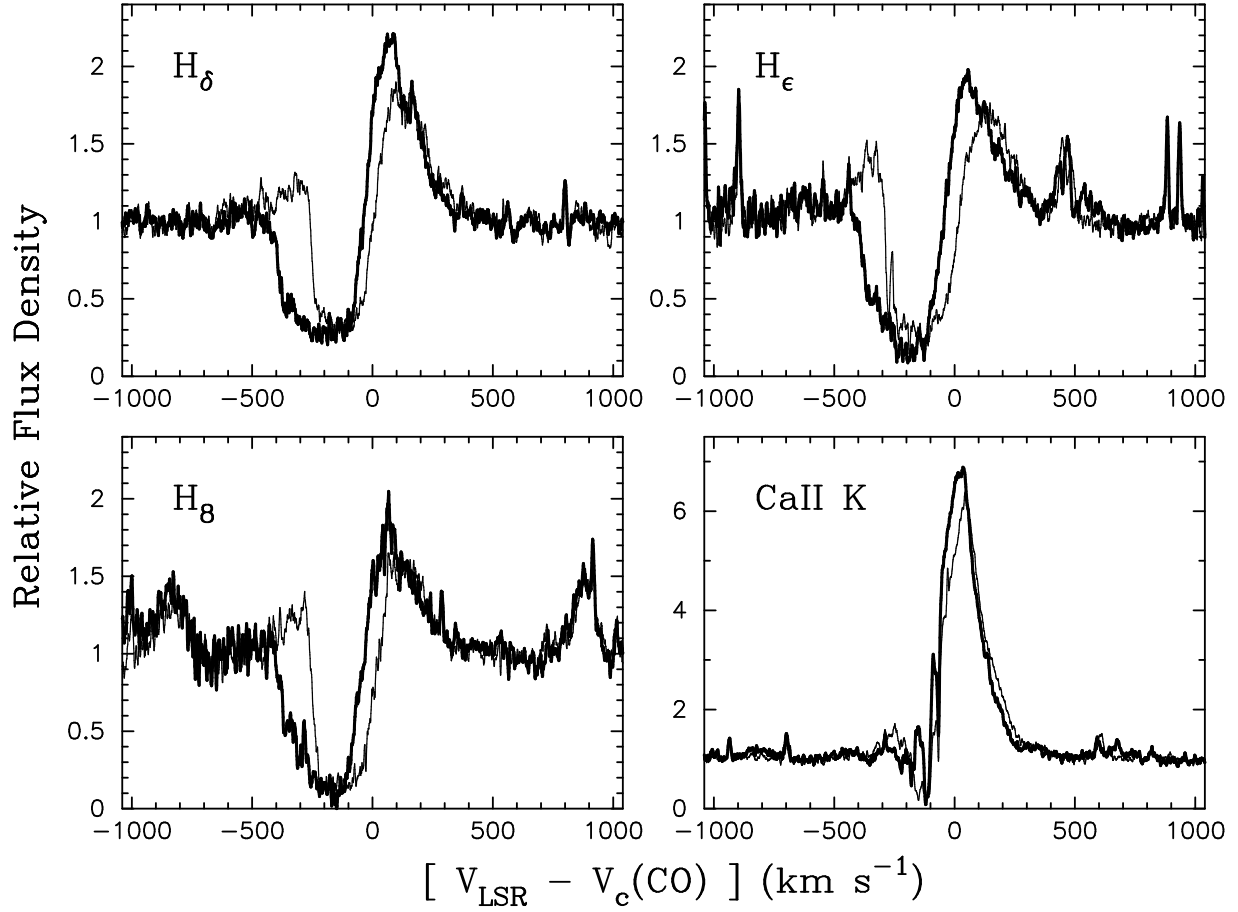


Fig. 2.— H_{δ} (top-left), H_{ϵ} (top-right), H_8 (bottom-left), and Ca II K (bottom-right) lines in BM Gem observed on January 29 (thick line) and April 14, 2001 (thin line), shown with the original resolution ($\lambda/\Delta\lambda$) of 50,000. The spectra are normalized to the local Paschen continuum. For H_{δ} the contribution of the carbon star spectrum was approximately subtracted. The profiles indicate that the gas expansion velocity in January was as large as 400 km s^{-1}